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CLIMATE
CHANGE
RESEARCH
REPORT
CCRR-07

Responding to
Climate Change
Through Partnership

Ontario

Geological Sequestration of Carbon Dioxide:

A Technology Review and Analysis of Opportunities in Ontario

Climate Change and MNR: A Program-Level Strategy and Action Plan

The following describes how the Ministry of Natural Resources works to contribute to the Ontario Government's commitment to reduce the rate of global warming and the impacts associated with climate change. The framework contains strategies and sub-strategies organized according to the need to understand climate change, mitigate the impacts of rapid climate change, and help Ontarians adapt to climate change:

Theme 1: Understand Climate Change

Strategy #1: Gather and use knowledge in support of informed decision-making about climate change. Data and information gathering and management programs (e.g., research, inventory, monitoring, and assessment) that advances our knowledge of ecospheric function and related factors and forces such as climate change are critical to informed decision-making. Accordingly, MNR will work to:

- Strategy 1.A: Develop a provincial capability to describe, predict, and assess the important short- (0-5 years), medium- (5-20 years), and long-term (20+ years) impacts of climate change on the province's ecosystems and natural resources.
- Strategy 1.B: Model the carbon cycle.

Strategy #2: Use meaningful spatial and temporal frameworks to manage for climate change. A meaningful spatial and temporal context in which to manage human activity in the ecosphere and address climate change issues requires that MNR continue to define and describe Ontario's ecosystems in-space and time. In addition, MNR will use the administrative and thematic spatial units required to manage climate change issues.

Theme 2: Mitigate the Impacts of Climate Change

Strategy #3: Gather information about natural and cultural heritage values and ensure that this knowledge is used as part of the decision-making process established to manage for climate change impacts. MNR will continue to subscribe to a rational philosophy and corresponding suite of societal values that equip natural resource managers to take effective action in combating global warming and to help Ontarians adapt to the impacts of climate change.

Strategy #4: Use partnership to marshal a coordinated response to climate change. A comprehensive climate change program involves all sectors of society as partners and participants in decision-making processes. The Ministry of Natural Resources will work to ensure that its clients and partners are engaged.

Strategy #5: Ensure corporate culture and function work in support of efforts to combat rapid climate change. Institutional culture and function provide a "place" for natural resource managers to develop and/or sponsor proactive and integrated programs. The Ministry of Natural Resources will continue to provide a "home place" for the people engaged in the management of climate change issues.

Strategy #6: Establish on-site management programs designed to plan ecologically, manage carbon sinks, reduce greenhouse gas emissions, and develop tools and techniques that help mitigate the impacts of rapid climate change. On-site land use planning and management techniques must be designed to protect the ecological and social pieces, patterns, and processes. Accordingly, MNR will work to:

- Strategy 6.A: Plan ecologically.
- Strategy 6.B: Manage carbon sinks.
- Strategy 6.C: Reduce emissions.
- Strategy 6.D: Develop tools and techniques to mitigate the impacts of rapid climate change.

Theme 3: Help Ontarians Adapt

Strategy #7: Think and plan strategically to prepare for natural disasters and develop and implement adaptation strategies. MNR will sponsor strategic thinking and planning to identify, establish, and modify short- and long-term direction on a regular basis. Accordingly, MNR will work to:

- Strategy 7.A: Sponsor strategic management of climate change issues.
- Strategy 7.B: Maintain and enhance an emergency response capability.
- Strategy 7.C: Develop and implement adaptation strategies for water management and wetlands.
- Strategy 7.D: Develop and implement adaptation strategies for human health.
- Strategy 7.E: Develop and implement adaptation strategies for ecosystem health, including biodiversity.
- Strategy 7.F: Develop and implement adaptation strategies for parks and protected areas for natural resource-related recreational opportunities and activities that are pursued outside of parks and protected areas.
- Strategy 7.G: Develop and implement adaptation strategies for forested ecosystems.

Strategy #8: Ensure policy and legislation respond to climate change challenges. Policy, legislation, and regulation guide development and use of the programs needed to combat climate change. MNR will work to ensure that its policies are proactive, balanced and realistic, and responsive to changing societal values and environmental conditions.

Strategy #9: Communicate. Ontarians must understand global warming, climate change, and the known and potential impacts in order to effectively and consistently participate in management programs and decision-making processes. Knowledge dissemination through life-long learning opportunities that are accessible and current is critical to this requirement. MNR will raise public understanding and awareness of climate change through education, extension, and training programs.

Geological Sequestration of Carbon Dioxide:

A Technology Review and Analysis of Opportunities in Ontario

Terry Carter[1], William Gunter[2], Michael Lazorek[3], Robert Craig[4]

[1] Ontario Ministry of Natural Resources, London, ON

[2] Alberta Research Council, Edmonton, AB

[3] Ontario Ministry of Natural Resources, London, ON

[4] ICO_2N Group, Calgary, AB

Ontario Ministry of Natural Resources
1235 Queen Street East
Sault Ste. Marie, Ontario
Canada P6A 2E5

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Telephone: (705) 946-2981
Fax: (705) 946-2030
E-mail: information.ofri@ontario.ca

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Abstract

Geological sequestration of carbon dioxide (CO_2), also known as carbon capture and storage (CCS), has been identified by the Intergovernmental Panel on Climate Change (IPCC) as having the potential to effect significant reductions in global anthropogenic emissions of CO_2. The panel recommends that CCS be included as part of a broad portfolio of greenhouse gas management strategies for mitigation of climate change.

CCS is a technical process that involves capturing CO_2 from large point sources, purifying the emissions to maximize the CO_2 content, and transporting the CO_2 to a storage site where it is injected, using a specially constructed well, into deep geological formations for permanent storage. Most components of the technology are proven and already in use in the petroleum industry but it is not yet in full-scale use in other industries primarily due to cost and lack of clear regulatory or policy direction from government. Research to improve this technology and lower the costs is underway in several countries.

While world governments debate a suitable legal, regulatory, and policy framework it is prudent to conduct geological research to identify suitable sites and geologic formations for storage of CO_2. In the United States, regional carbon sequestration partnerships funded by the Department of Energy have been conducting this type of research since 2003, with industries, state governments, and some Canadian provinces involved as partners. No similar research is presently being conducted in Ontario.

Southern Ontario is located on the edge of two of the largest sedimentary basins in eastern North America, the Michigan and Appalachian Basins. Preliminary studies have indicated the potential to store up to 730 Mt of CO_2 in saline aquifers in deep geologic formations in the portions of these basins located within southern Ontario, with considerable additional potential in neighbouring U.S. states. Further research is necessary to assess Ontario's geological capacity and suitability for storage, identify possible risks, and find the best potential sites for injection of CO_2 into the subsurface.

Résumé

La séquestration géologique du dioxyde de carbone : évaluation technologique et analyse des possibilités en Ontario

Le Groupe d'experts intergouvernemental sur l'évolution du climat a indiqué que la séquestration géologique du dioxyde de carbone (CO_2), une technique aussi appelée « capture et stockage de carbone (CSC) », pouvait considérablement influer sur la réduction des émissions anthropiques de CO_2 à l'échelle mondiale. Le Groupe recommande d'intégrer la technique de CSC dans une vaste gamme de stratégies de gestion des gaz à effet de serre afin d'atténuer les changements climatiques.

La technique de CSC est un processus qui consiste à capturer le CO_2 émis par de grandes sources ponctuelles, à purifier les émissions de façon à en maximiser la teneur en CO_2 et à transporter le CO_2 ainsi emprisonné dans un site de stockage où il est injecté, à l'aide d'un puits construit spécialement à cet effet, dans des formations géologiques souterraines où il sera conservé de façon permanente. La plupart des composants de la technologie sont approuvés et actuellement utilisés dans l'industrie pétrolière, contrairement à d'autres secteurs où le procédé est peu employé en raison, principalement, des coûts et du manque de clarté dans le processus de réglementation ou de l'absence d'une orientation gouvernementale précise en matière de politique. Des recherches visant à améliorer cette technologie et à en réduire les coûts sont en cours dans plusieurs pays.

Pendant que les gouvernements de tous les pays discutent de l'adoption d'une loi, d'une réglementation et d'une politique pertinentes, nous jugeons prudent de procéder à des recherches sur le plan géologique afin d'identifier les sites et les formations géologiques qui se prêtent au stockage du CO_2. Aux États-Unis, des partenariats régionaux pour la séquestration du carbone, financés par le département de l'Énergie, mènent ce type de recherches depuis 2003 avec, comme partenaires, des industries, les administrations de certains États et quelques provinces canadiennes. Aucune recherche semblable n'est actuellement entreprise en Ontario.

Le territoire du Sud de l'Ontario longe deux des plus grands bassins sédimentaires de l'est de l'Amérique du Nord, les bassins de Michigan et des Appalaches. Selon des études préliminaires, on pense qu'il est possible de stocker un maximum de 730 Mt de CO_2 dans les aquifères salins se trouvant dans des formations géologiques souterraines, dans les portions de ces bassins situées à l'intérieur du territoire du Sud de l'Ontario. De plus, d'autres sites de grande importance appartenant aux États américains voisins pourraient également servir à cette fin. Il est proposé que l'Ontario se joigne au partenariat américain *Midwest Regional Carbon Sequestration Partnership* et dirige un programme d'études approfondies des sciences de la Terre portant sur la technique de CSC en Ontario, et plus particulièrement sur les aquifères salins dans les grès de la formation de Mount Simon, sous les lacs Érié et Huron. Disposant d'une infrastructure industrielle et doté d'une communauté scientifique et technique chevronnée, l'Ontario aurait alors l'occasion d'acquérir un savoir-faire et de devenir éventuellement un chef de file mondial en matière de technologie de séquestration de CO_2.

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Introduction

From 1994 to 2004 world primary energy production increased at an annual rate of 2.2% (Energy Information Administration 2006a). Carbon dioxide (CO_2) emissions during this period increased at the same rate, rising from 21.7 Gt (gigatonnes) in 1994 to 27.0 Gt in 2004. In 2004 fossil fuels accounted for 86% of world primary energy production while renewable fuels accounted for only 8% (Energy Information Administration 2006b). Even with recent rapid development of renewable energy, in particular the generation of electricity from wind power, fossil fuels will continue to dominate world energy production and consumption until at least 2050 (Hughes 2005, Metz et al. 2005).

According to the Auditor-General of Canada (2006) "energy production and consumption account for more than 80 percent of the greenhouse gas emissions in Canada". Thus Canadians must change the way they produce, distribute, and consume energy if they hope to achieve meaningful reductions in greenhouse gas emissions to the atmosphere. Geological sequestration of CO_2, also referred to as carbon capture and storage (CCS) technology, offers a promising tool for managing greenhouse gas emissions from the continued use of fossil fuels until new sources of energy can be developed. According to the Intergovernmental Panel on Climate Change (IPCC) "the potential of CO_2 capture and geological storage is considerable, and the costs for mitigating climate change can be decreased compared to strategies where only other climate change mitigation options are considered" (Metz et al. 2005).

This report reviews the current state of knowledge of this technology and its status, both nationally and worldwide, and the opportunities for CO_2 sequestration in geological formations in the province of Ontario. With its available geologic storage capacity close to large industrial point sources of CO_2, proven infrastructure and highly trained scientific and technical community, Ontario has the potential to become a world leader in carbon sequestration technology while making meaningful reductions in CO_2 emissions to the atmosphere.

Options to Reduce Anthropogenic Carbon Dioxide Emissions to the Atmosphere

Reducing anthropogenic CO_2 emissions into the atmosphere can be achieved by a variety of means, summarized by a form of the Kaya equation:

$$\mathbf{CO_2\Uparrow = POP \times GDP/POP \times BTU/GDP \times CO_2\Uparrow\Uparrow/BTU - CO_2\Downarrow}$$

where $CO_2\Uparrow$ is the total CO_2 released to the atmosphere, POP is population, GDP/POP is per capita gross domestic product and is a measure of standard of living, BTU/GDP is energy consumption per unit of GDP and is a measure of energy intensity, $CO_2\Uparrow\Uparrow$/BTU is the amount of CO_2 released per unit of energy consumed and is a measure of carbon intensity, and $CO_2\Downarrow$ is the amount of CO_2 stored in biosphere and lithosphere sinks (Gunter et al. 1998). There are a number of carbon management options available including reducing emissions, reducing energy and carbon intensity, and increasing carbon sequestration.

A very attractive and cost-effective solution to reduce energy intensity is energy conservation. This approach involves improving energy and material efficiency or modifying industrial processes, thus lowering the rate of CO_2 generation. This also provides an overall payback in the form of lower energy expenditures over time. One option to reduce carbon intensity is to increase the use of renewable resources. However, until such energy sources can be developed and applied on a large scale, fossil energy resources will continue to be the primary energy sources around the globe. During this period, carbon intensity could be reduced by switching to low carbon alternative fuels (e.g., natural gas or nuclear from oil, coal or other higher carbon fuel sources). While these options are probably solutions for the long term, short- and medium-term solutions are needed to minimize CO_2 emissions. Reducing

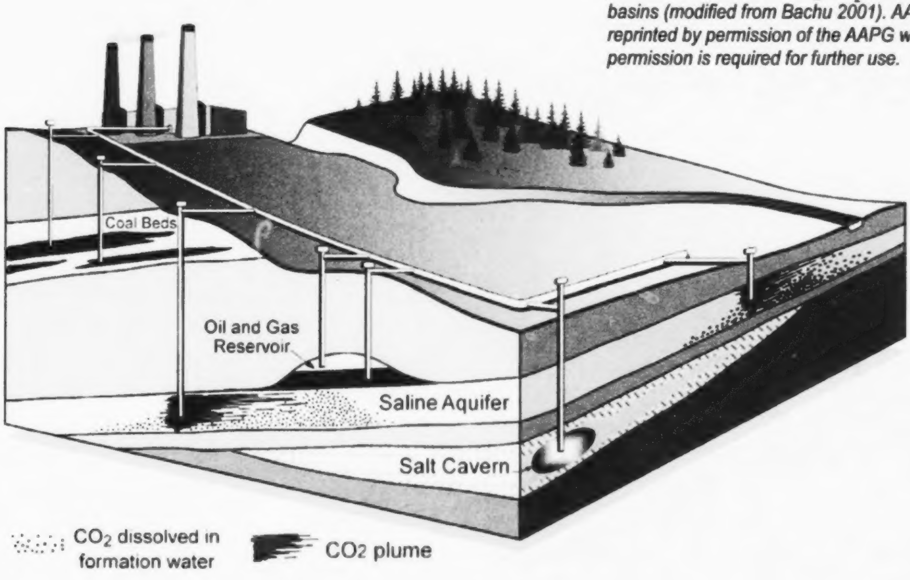
emissions is a complex issue, and can only be solved by innovative responses that include both reducing the quantities of these gases emitted by anthropogenic activities, and enhancing and maximizing the use of greenhouse gas sinks through carbon sequestration in the biosphere, in materials, and in the lithosphere.

What is Carbon Dioxide Capture and Geological Storage in Sedimentary Basins?

Carbon dioxide capture and storage is a technical sequestration process that involves the capture and transportation of CO_2 and its storage in geological formations in sedimentary basins in the geosphere (Figure 1) where water, oil, and gas were initially stored (and to some degree remain present). Of the igneous, metamorphic, and sedimentary rocks that constitute the Earth's crust or lithosphere, sedimentary rocks in sedimentary basins contain the largest volume of pore space in which CO_2 could be stored (Figure 2).

Sedimentary rocks occur in sedimentary basins formed by accumulation of sediments in large-scale depressions in the Earth's crust that subsequently undergo burial, compaction, lithification, and uplift over millions of years. As the sediments are buried, they start to compact and dewater in the earlier stages of the lithification process. Eventually the grains consolidate as a result of increasing temperature and pressure, cement together as a result of various physical and geochemical processes, and become rock (e.g., sandstone, siltstone, shale, limestone, and halite). The coarser-grained sedimentary rocks, such as sandstone, usually have highly interconnected pore space (porosity) allowing for fluid flow (permeability), although carbonate rocks, particularly reefs, can also have significant permeability. The finer grained sedimentary rocks, such as shales, have poorly interconnected pore space and much lower permeability and can act as very effective barriers to flow. Evaporitic rocks (halite and anhydrite) have extremely low permeability. As a result of various tectonic, depositional, and erosional processes, sedimentary basins have a plumbing system defined by the superposition of these high (aquifers) and low (aquitards, and aquicludes) permeability strata that control fluid movement (Figure 3).

Figure 1. Diagrammatic representation of the possible methods of storing CO_2 in sedimentary basins (modified from Bachu 2001). AAPG©2001, reprinted by permission of the AAPG whose permission is required for further use.



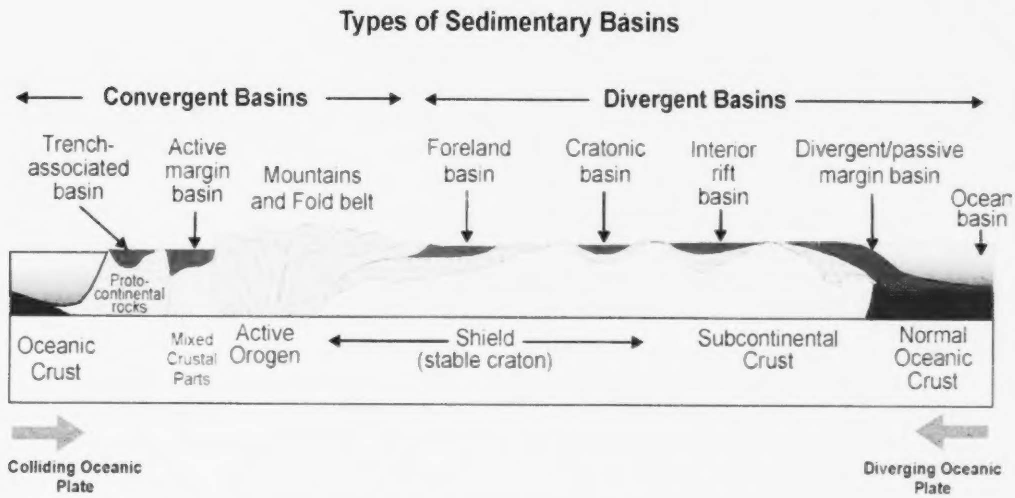


Figure 2. *Illustration of the various types of sedimentary basins across North America in relation to the igneous and metamorphic rocks of the crust (from Hitcheon et al. 1999). Horizontal scale = 1000s of km; vertical scale = 10s of km.*

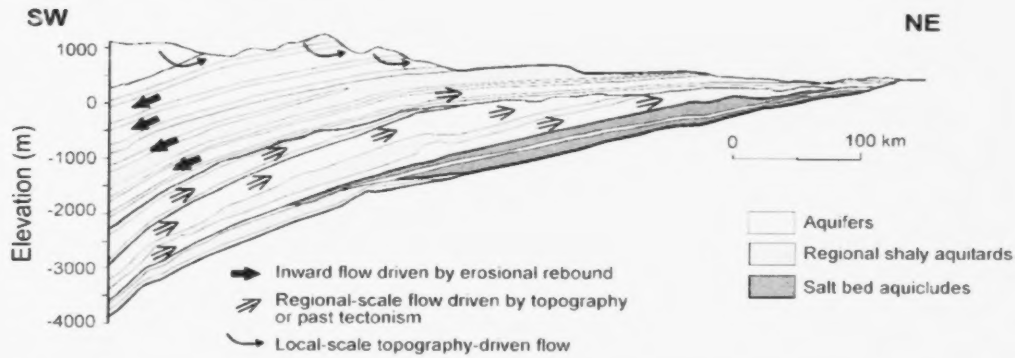


Figure 3. *Diagrammatic cross-section through the Alberta sedimentary basin showing main flow types and systems (after Bachu 1995). AAPG©1995, reprinted by permission of the AAPG whose permission is required for further use.*

One of the more promising avenues of research has been the storage of CO_2 in saline aquifers deep in sedimentary basins. Of the various methods that have been suggested for CO_2 storage in sedimentary basins (in oil and gas reservoirs to enhance oil recovery, in geological structures such as salt domes, in depleted oil and gas reservoirs, in coal beds, and in aquifers), aquifers have the largest capacity (Figure 3). The volume of pore space available in deep saline aquifers far exceeds that of enhanced oil recovery projects, salt domes, or depleted hydrocarbon reservoirs. Aquifers were the conduit for the movement of oil and gas into their present reservoirs in the Earth's crust. Oil and gas reservoirs are often sedimentary traps formed from aquifers by plugging, faulting or folding of the aquifer, and thus constitute only a small part of the total. Further, aquifers are widely distributed and, most important, underlie and are located proximal to most point sources of CO_2 emission (Figure 1).

Carbon dioxide is ideal for aquifer storage because of its high density and high solubility in water at the relatively high pressures that occur at depths greater than 800 m. At present, this technology is economically viable only where an environmental cost or penalty is avoided by sequestering the CO_2, such as in the Norwegian sector of the North Sea.

In addition to storing it in saline aquifers, CO_2 may also be injected into oil and gas reservoirs. This may occur in three situations. First, because CO_2 is a miscible solvent with oil, oil recoveries can be increased substantially through miscible flooding of the reservoir (termed enhanced oil recovery, or EOR). In effect, the residual oil is washed from the reservoir rock by the CO_2 solvent. The oil-CO_2 mixture is separated at the surface and the oil is used as fuel in the normal way. The CO_2 that is returned to the surface can then be re-used for more oil recovery or disposed of in deep saline aquifers. This type of EOR has been active in the U.S. for over 25 years, not as an environmental strategy, but to improve recovery from oilfields as they near the end of their economic life. In Canada, EOR is likely the primary and most economic use for CO_2, though other end uses will become more viable as technology develops. Secondly, CO_2 may be used to displace natural gas in depleted gas reservoirs, known as enhanced gas recovery (EGR). Commercial adoption of CO_2 as an enhanced recovery agent for either gas reservoirs or coal bed methane has not yet occurred. The recycling of gases in EOR and EGR is possible because of the close association of the fossil fuel resources of sedimentary basins and the greenhouse gas-emitting industry based on those fuels. Thirdly, CO_2 may be injected into depleted oil and gas reservoirs, under the principle that the hydrogeological conditions that allowed the hydrocarbons to accumulate initially will also permit the accumulation of CO_2 in the space vacated by the produced hydrocarbons. Intuitively, the carbon removed as oil and gas can be returned as CO_2.

In summary, a strong association exists between sedimentary basins and fossil fuels. Those basins with fossil fuel deposits that are being exploited characteristically have high CO_2 emissions. Any specific basin may be a prolific hydrocarbon producer or not, depending on its geologic history. Common to all sedimentary basins is the fluid that effectively fills most of the pore spaces—saline formation water. Despite their dominant economic importance, oil and gas are rare fluids in terms of their volume in sedimentary basins. Thus, formation water (and the space it occupies), rather than oil and gas, is important for aquifer storage of CO_2. Consequently, geological storage introduces a need for understanding the large-scale aquifer systems of the basin to ensure secure, long-term CO_2 storage and to avoid leakage to the atmosphere through transmissive faults, fractures or abandoned well-bores.

An investigative strategy is therefore to (1) identify the point sources of CO_2 emission, (2) conduct a detailed, regional-scale hydrogeological analysis of the basin to identify suitable storage aquifers that satisfy the conditions of depth, capping, permeability, CO_2 solubility and storage capacity, and (3) carry out detailed hydrogeological, injectivity and geochemical studies for aquifers near the CO_2 sources. If these studies meet all the technical and regulatory criteria for CO_2 storage, and government policy and economic incentives for large-scale CO_2 reduction are suitable, then design of pilot and commercial CO_2 storage facilities can be finalized, the infrastructure and field facilities built, and CO_2 injection into storage reservoirs initiated.

National and International Context

Carbon dioxide storage in low permeability, deep saline aquifers in sedimentary basins is technically feasible and perhaps offers the largest potential for CO_2 storage in the landlocked areas of the world. In the Sleipner Vest gas field in the North Sea, about 1 million tonnes per year of CO_2 is removed from the natural gas and injected into sandstones of the 250-m thick Utsira Formation about 1000 m below the sea bed. Injection started in September 1996. The cost of capture and injection rather than venting is economically justified to avoid a Norwegian tax of approximately $50 Cdn per tonne of CO_2 emitted to the atmosphere in offshore oil and gas operations. In Western Australia, the Gorgon project plans to inject approximately 10 million tonnes annually

of waste CO_2 from a natural gas liquification plant into the offshore Dupuy aquifer. An even larger project is the proposed removal of the 71% CO_2 in the natural gas of the Natuna Field in Indonesia—one of the largest gas fields in the world with reported 1270 billion cubic metres of recoverable hydrocarbon reserves. Waste gas will be injected into two carbonate aquifers near the Natuna Field. If the plan goes ahead, construction of the facilities will take eight years. Both these projects await an appropriate fiscal and environmental regime before the private sector will proceed.

Worldwide, CO_2 is used for EOR in more than 70 projects, mainly relying on naturally occurring sources. In the U.S. more than 100,000 tonnes of CO_2 are used annually for EOR. In Canada, availability, cost, and government policy have favoured the use of hydrocarbons such as ethane or liqified petroleum gas mixes over CO_2 as a miscible solvent. However, EnCana Ltd. of Calgary, Alberta is purchasing CO_2 from the Great Plains coal-gasification plant at Beulah, North Dakota. The plant produces pipeline quality synthetic natural gas, and other products, by gasification of lignite from local mines. The CO_2 (up to 13,000 tonnes/day) is piped 330 km to be used for EOR in the Weyburn oil field, Saskatchewan. This is the largest EOR operation in Canada and will extend the life of the field as much as 25 years, while at the same time storing a million tonnes of CO_2 annually in the oil reservoir. This association of using available, low-cost waste CO_2 at a distant oil field for EOR is economically viable after expenditures of more than a billion dollars—surely one of the best illustrations of the possible synergies of "waste and want" in sedimentary basins.

If CO_2 is injected into the gas cap of an oil reservoir, not only is gas recovery enhanced by re-pressurization but additional pressure is provided for oil recovery. In the oil sand deposits of Alberta, the production rate and recovery of bitumen during steam-assisted gravity drainage (SAGD) can be affected by the production of natural gas from associated reservoirs. Re-pressurizing the gas reservoirs with CO_2 may also enhance the economic production of bitumen.

If CO_2 is injected into the base of a depleted gas reservoir, being denser than the natural gas, it will displace the remaining gas upwards to an appropriately placed production well. Although shown to work in theory, the economic viability of this approach is not yet evident and commercial operations do not yet exist.

The advantages of using CO_2 for EOR/EGR operations by injecting it into depleted oil and gas reservoirs are:

(1) Hydrocarbon production sites and reservoirs suitable for carbon dioxide injection are in close proximity.

(2) Geological processes that allowed the accumulation of hydrocarbons also permit the secure sequestering of injected CO_2.

(3) The benefits of EOR can offset some of the cost of capturing, transporting, and injecting CO_2.

(4) The technology and infrastructure for oil and gas production can be adapted for CO_2 injection; this ranges from knowledge of exploration for and production from reservoirs, through all aspects of gas separation, handling high pressure fluids, and pipelining, to ensuring safe operations and appropriate environmental studies.

Several studies conducted over the past decade have estimated how much CO_2 can be stored in sedimentary basins in depleted oil and gas reservoirs, unmineable coal seams, and deep saline aquifers (International Energy Agency 1995). More recently, Bachu and Adams (2003) estimated the ultimate CO_2 sequestration capacity in two deep saline aquifers in western Canada at approximately 170 Gt (gigatonnes). Since no generally accepted method exists to estimate the storage capacity of a particular formation, each of these studies used a different approach. Nevertheless, as shown in Table 1, there is general agreement on several important issues. First, global storage capacity is greater than 1000 GtC (gigatonnes of carbon or 3667Gt of CO_2). Second, saline aquifers have the greatest capacity, followed by oil and gas reservoirs and unmineable coal seams. Third, potentially suitable formations are distributed throughout the world. These conclusions are supported by the recent IPCC (Metz et al. 2005) report on CCS.

Table 1: Estimated carbon storage capacity of selected sedimentary basins (International Energy Agency 1995, Gunter et al. 1998)

Storage Type	Global Capacity	U.S. Capacity	Canadian Capacity
	(Gigatonnes carbon)	(Gigatonnes carbon)	(Gigatonnes carbon)
Depleted oil reserve	40-190	10-14	0.6
Depleted gas reserve	140-310	20-30	4
Saline aquifers	87-2700	1-130	>10
Unmineable coal	5-40	4-5	4

Although initial injection of CO_2 into sedimentary basins will likely be into oil and gas reservoirs, in the long term and for the reasons noted above, the deep saline aquifers in the basins will be the ultimate sink for CO_2. These aquifers have an overwhelmingly greater capacity, and they occur throughout all sedimentary basins, at all depths, with a wide variety of lithologies. Further, it should be possible to locate a suitable aquifer close to CO_2 sources, unlike hydrocarbon reservoirs, which are scarce in some sedimentary basins.

A number of international consortia have been formed to accelerate the commercialization of CCS. The oldest is the International Energy's Greenhouse Gas Research and Development Program begun 15 years ago. Led by the U.S., the Carbon Sequestration Leadership Forum was formed in 2003 to identify policy and technology options. Canada is a member and has leadership roles in both these initiatives. The Asia-Pacific 6 (USA, Australia, India, China, Japan and Korea) was formed recently to apply CCS in developing countries, mainly targeting China and India. As well, a United Kingdom-European Union initiative is underway to develop a CCS demonstration in China over the next 10 years. FutureGen in the U.S. is planning to build an integrated gasification combined cycle (IGCC) power plant with CCS.

The U.S. has formed seven Regional Carbon Sequestration Partnerships to work on studies, pilots, and plans for a CCS demo with support from the U.S. Department of Energy. In Canada, the Canadian Clean Power Coalition has been evaluating oxyfuel and gasification as technologies that deploy CCS and replace conventional combustion of coal. The Integrated Carbon Dioxide Network (ICO_2N), a partnership of Canadian oil, natural gas, power, and industrial CO_2 emitters, was formed to evaluate and promote CCS commercialization in Canada. In parallel, a number of national CCS roadmaps have been developed, including those on CCS and Clean Coal for Canada developed through Natural Resources Canada (2005, 2006b) and planning documents by Alberta Environment for CO_2 capture (CANiCAP) (Gunter et al. 2005) and geological storage (Gunter and Chalaturnyk 2004, Gunter and Lakeman 2006) (CANiSTORE). All are available on the website of the Canadian CO_2 Capture and Storage Technology Network (CCCSTN).

The IPCC (2005) issued a special report on CCS in 2005. Asia Pacific Economic Cooperation, using Canadian expertise, has developed CCS capacity building workshops given in China in 2006 and scheduled for Mexico in 2007. Also of note is a book by Marc Jaccard (2005) of Simon Fraser University entitled "Sustainable Fossil Fuels: The Unusual Suspect in the Quest for Clean and Enduring Energy," which advocates CCS as a major option for meeting greenhouse gas reduction targets. Finally, the National Roundtable on Energy and the Environment issued a report in 2006 that advocated CCS as a key strategy for Canada in pursuing GHG reductions. The major delay in commercialization of CCS is the lack of policy to provide the necessary legal and economic incentives for implementation.

Carbon Dioxide Capture Technology Overview

Large-scale CO_2 capture involves several unique physical processes and chemical reactions, which ultimately produce a relatively pure form of CO_2 suitable for transportation to an array of end-uses. The purity of the CO_2 is dependent on its end-use – EOR usage purity is typically greater than 98%. For geological storage, purity can be significantly less. Technical considerations include the removal of all water to avoid severe corrosion of metal pipes and valves and CO_2 must be compressed to a liquid or semi-liquid state to be economically transported by pipeline to its final destination.

A variety of capture processes are at various stages of technical readiness and commercial viability. These technologies deliver streams of high-purity CO_2 which can be compressed, transported, and delivered to an end-use market or suitable sequestration location. These processes are complex, capital intensive and generally are integrated with an existing set of facilities. Capturing CO_2 involves using existing processes in a new way or developing a new combination of process steps. Rarely does CO_2 capture incorporate totally new technology.

The three major types of capture technology (Metz et al. 2005) are post-combustion, pre-combustion and oxyfuel capture (Figure 4).

Post-combustion capture requires separation of CO_2 from a mixture of elements created through combustion, principally nitrogen, water vapour, small amounts of unburned oxygen, and various other compounds. The CO_2 purity in a post-combustion environment is typically very low, between 5 and 15% depending on the fuel source, which hampers economic capture. Also, this environment is water saturated and at low pressure. This complicates the process and adds cost. Post-combustion capture uses available technology now used in both power plants and natural gas processing plants around the world.

Pre-combustion capture removes CO_2 from the inlet fuel stream prior to combustion. A key advantage to this approach is that CO_2 can be captured more economically and readily prior to combustion, given higher

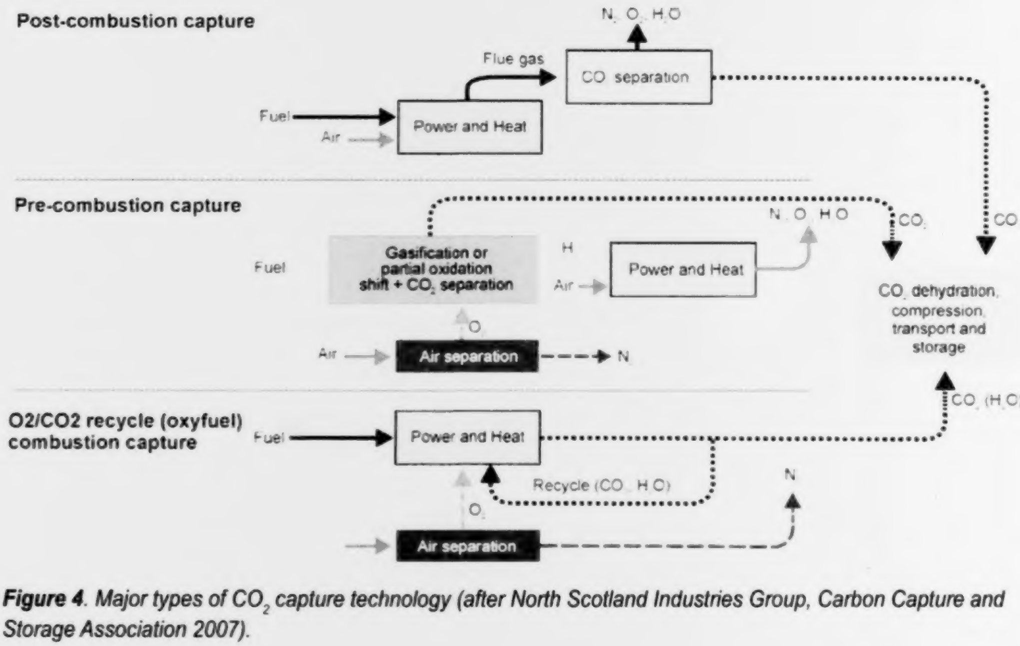


Figure 4. Major types of CO_2 capture technology (after North Scotland Industries Group, Carbon Capture and Storage Association 2007).

concentrations of CO_2 and higher pressures. Examples of this are steam methane reforming and gasification, both of which are used to create hydrogen from hydrocarbon sources and produce CO_2 as a waste stream. Steam methane reforming uses available technology, whereas gasifiers are an emerging technology.

Oxyfuel combustion capture involves air separation to decrease nitrogen and increase oxygen at the inlet to the combustion process. This reduces the mass flow through the combustion stream and results in a higher percentage of CO_2 in the combustion product. Application of this technology to existing processes requires changes in combustion features – a new furnace design or a CO_2 recycle loop at moderate temperatures. Of the three capture technologies, oxyfuel combustion is the least advanced technology. Demonstration plants have been built to test it on a non-commercial scale. A project recently announced by Saskatchewan's primary energy utility, SaskPower, would build the first commercial-scale oxyfuel power plant in North America.

Lastly, CO_2 is sometimes available as a waste product from industrial sources, for example, both CO_2 and sulphur dioxide occur at relatively high concentrations in natural gas production from some hydrocarbon reservoirs. The CO_2 is removed to render the natural gas saleable resulting in a relatively high purity CO_2, which could be captured for use in downstream markets. Presently, it is either vented to the atmosphere or injected into disused oil reservoirs as acid gas disposal. Natural gas reservoirs in Ontario do not have elevated concentrations of CO_2.

Technical Requirements for Geological Storage of Carbon Dioxide

Rock formations suitable for storage of CO_2 include coal beds, organic shales or rocks with large amounts of interconnected pore space (i.e. porosity and permeability) (Figure 5). This not only creates the space required to store the CO_2, but also allows it to migrate away from the injection point. Crystalline igneous and metamorphic rocks tend to have limited interconnected porosity. Sedimentary rocks such as sandstones, dolostones, and limestones have more potential for interconnected porosity. In addition, limestones and dolostones can undergo chemical alterations, which either increase the pore space through dissolution of existing minerals or result in precipitation of new mineral grains with permanent sequestration of CO_2. The porosity and permeability of geological formations in the subsurface vary greatly making it is necessary to map their distribution with some degree of detail and confidence when considering storage capacity and feasibility.

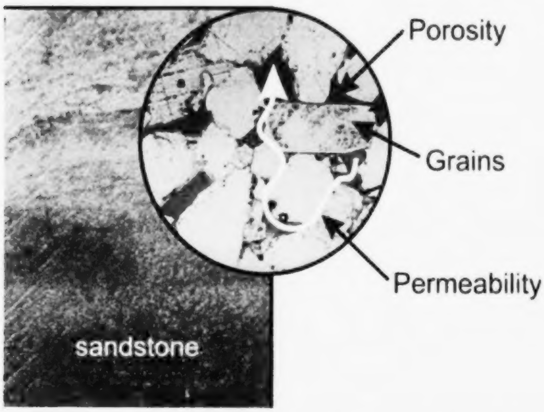


***Figure 5**. Porosity (pore space) and permeability (potential for flow) within sandstone rock.*

In addition to porosity and permeability, other important characteristics of the storage formation include the presence of a suitable impermeable cap rock, a pressure and temperature regime suitable for injection and storage of CO_2 in a "supercritical" or liquid phase, proximity to an infrastructure capable of delivering CO_2 to the injection site and a well-characterized migration route for the sequestered gas. Potential risks must also be characterized, with special attention paid to seismic activity, faults, fractures, and unplugged well-bores that could provide a pathway for CO_2 to escape to the surface.

Finally, any effects on proven and potential oil and gas reservoirs must be evaluated.

To maximize storage, CO_2 must be injected in a liquid or semi-liquid (supercritical) state. At normal atmospheric conditions CO_2 is a very stable gas and is heavier than air. In high pressure and low temperature environments, however, the supercritical phase of CO_2 has a density and viscosity approaching that of water. These conditions allow for a maximum volume of CO_2 to be injected and also increase the solubility within the formation water allowing maximal dispersal. High pressure-low temperature environments are common in sedimentary basins as the depth approaches 1,000 m. However, both temperature and pressure can be highly variable, requiring careful study and characterization. Initial estimates are that supercritical conditions for CO_2 storage in southwestern Ontario occur at a minimum depth and temperature of 865 m and 31.1°C, respectively (Shafeen et al. 2004a, Figure 6).

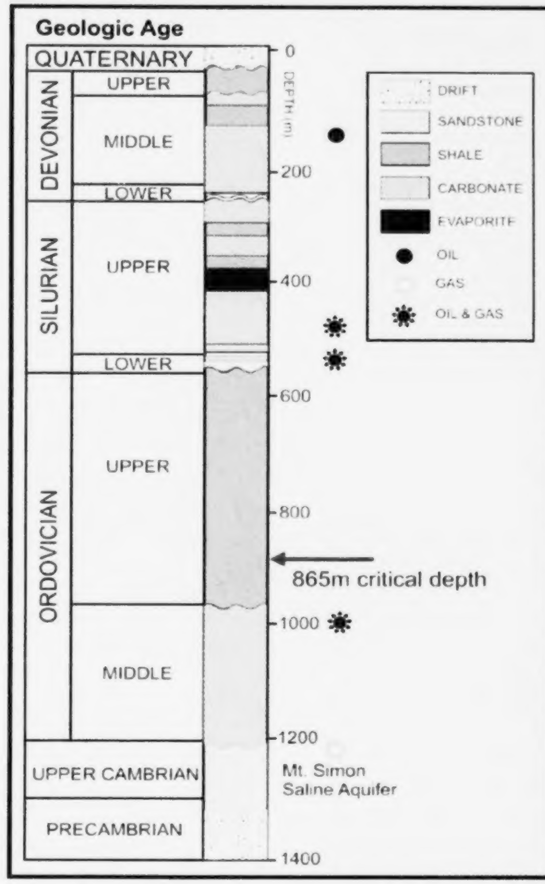


Figure 6*. Idealized stratigraphic section through Paleozoic rocks in the Sarnia area of Ontario. Supercritical conditions for storage are met below a depth of 865 m (from Shafeen et al. 2004a).*

Geological Sequestration Opportunities in Ontario

Point Source Emitters in Ontario

In relative proximity to Ontario's potential storage basins are several point source emitters of CO_2 that could potentially pursue CO_2 capture. In 2003 Ontario was responsible for 206 megatonnes (Mt) of Canada's overall CO_2 emissions of 740 Mt. Of the Ontario emissions 77 Mt were from the industrial group classified as *large final emitters* and 45 Mt of these emissions occurred in the Hamilton to Sarnia corridor (Table 2). It is important to note

Table 2*: Carbon dioxide emissions from large point sources in the Hamilton to Sarnia corridor, southern Ontario, in 2003 (Environment Canada 2007).*

COAL FIRED ELECTRICITY			
OPG Nanticoke 14.7 Mt	OPG Lambton 7.2 Mt		
GENERAL INDUSTRY			
Hamilton	**Sarnia**	**Nanticoke**	**London Area**
Dofasco 4.9 Mt	Petroleum 3.5 Mt	Stelco 3.5 Mt	Cement 1.0 Mt
Stelco 3.5 Mt	Chemicals 2.6 Mt	Petroleum 1.2Mt	Other 1.6 Mt
Carmeuse 0.6 Mt	TransAlta 1.3 Mt		

that the Nanticoke and Lambton coal-fired generating stations are scheduled to be closed in the next few years, thus reducing Ontario's annual CO_2 emissions by 21.9 Mt.

The location of large, single point-source emissions is a preliminary indicator of capture potential. Carbon dioxide capture feasibility and costs will vary for each location and depends upon type of industrial operation, fuel source, and age. These factors influence the nature and availability of CO_2. More work is required to test the feasibility and cost of capture at these locations.

Geology of Ontario

For the purpose of CO_2 storage, the geology of Ontario can be divided into three generalized rock types (Figures 7 and 8). The lowermost and oldest rocks consist of Precambrian rocks of the Canadian Shield, which underlie most of the North American continent and formed more than one billion years ago. Overlying the Canadian Shield to the north and to the south are younger sedimentary rocks. These range from 540 to 360 million years old and were deposited in sedimentary basins when Ontario was flooded by shallow tropical seas. The final uppermost layer consists of thin deposits of largely unconsolidated sediment or "drift" deposited during the last million years, largely as a result of glaciation.

The rocks of the Canadian Shield consist of either igneous rocks (cooled directly from magma) or metamorphic rocks (igneous or sedimentary rocks that have undergone intense deformation due to pressure and heat). Except where they have been fractured, these rocks have low porosity and permeability and are generally unsuitable for CO_2 storage. The unconsolidated sediments of the uppermost layer have good porosity and permeability, however, these sediments are open to the atmosphere, are major sources of potable groundwater and are very thin. This leaves Paleozoic rocks for consideration. These occur in the far north and in southern Ontario (Figure 7).

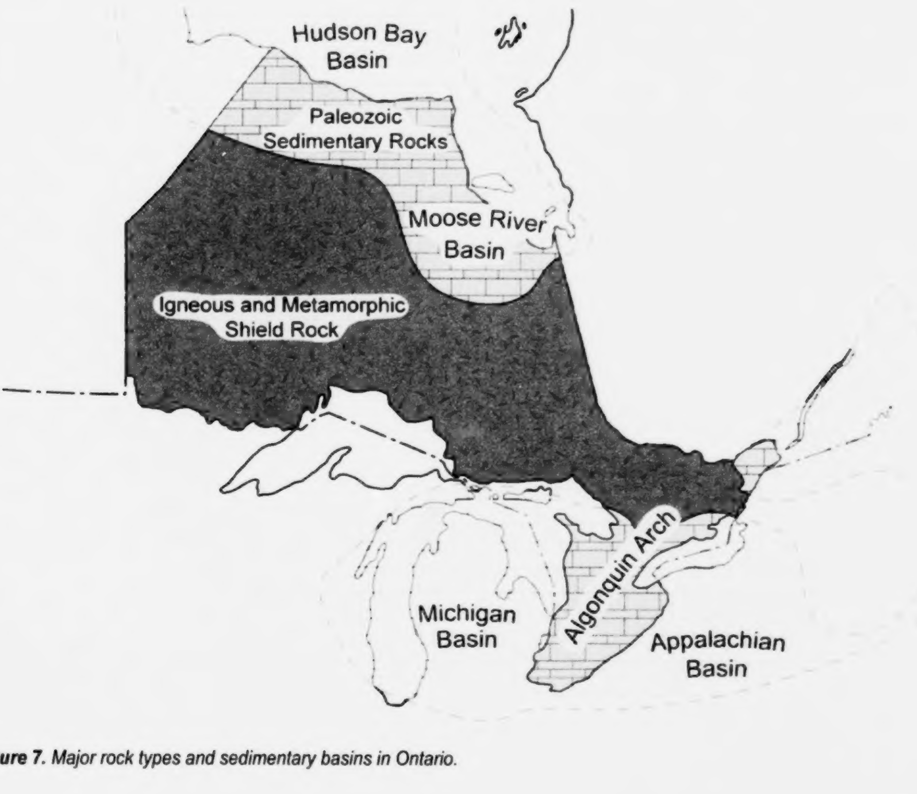


Figure 7. *Major rock types and sedimentary basins in Ontario.*

Four major sedimentary basins occur within Ontario (Figure 7). In northern Ontario, sedimentary rocks occur within the Moose River and Hudson Bay basins. These basins tend to be too shallow for carbon storage, reaching depths of approximately 500 m in the Moose River Basin and 1000 m in the Hudson Bay Basin. They are also remote from large point sources of CO_2 emissions and thus are presently impractical for consideration as candidates for geological sequestration. In southern Ontario, thick accumulations of sedimentary rocks are present in the Michigan and Appalachian basins. Rocks within these basins were originally horizontal, but have subsequently tilted and deformed forming a northeast-trending ridge known as the Algonquin Arch (Figure 9). Because of this, the thickness of the rocks increases westerly into the Michigan Basin and southerly into the Appalachian Basin, reaching a maximum thickness of about 1400 m beneath Lake Erie and at the southern tip of Lake Huron, and much greater thicknesses beneath the neighbouring U.S. states (Figures 8 and 9). Extensive development of porosity and permeability is evidenced by the presence of oil and gas reservoirs and regional saline water aquifers in these basins.

The sedimentary rocks within the Michigan and Appalachian basins are distinguished by geologic age and further subdivided into formations that can be mapped in the subsurface (Figure 10). The oldest and lowermost rocks are of Cambrian age and consist mainly of sandstones. Younger sandstone, shale, limestone, and dolostone rocks of Ordovician, Silurian, and Devonian age overlie the Cambrian rocks.

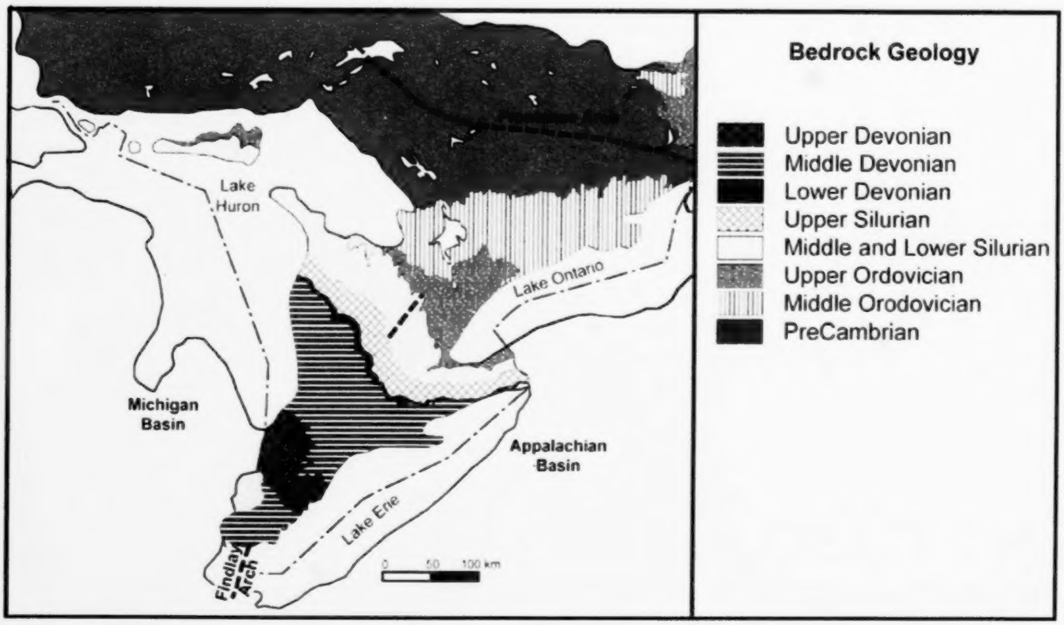


***Figure 8.** Subcrop of Paleozoic bedrock in southwestern Ontario (based on Armstrong and Carter 2006a,b).*

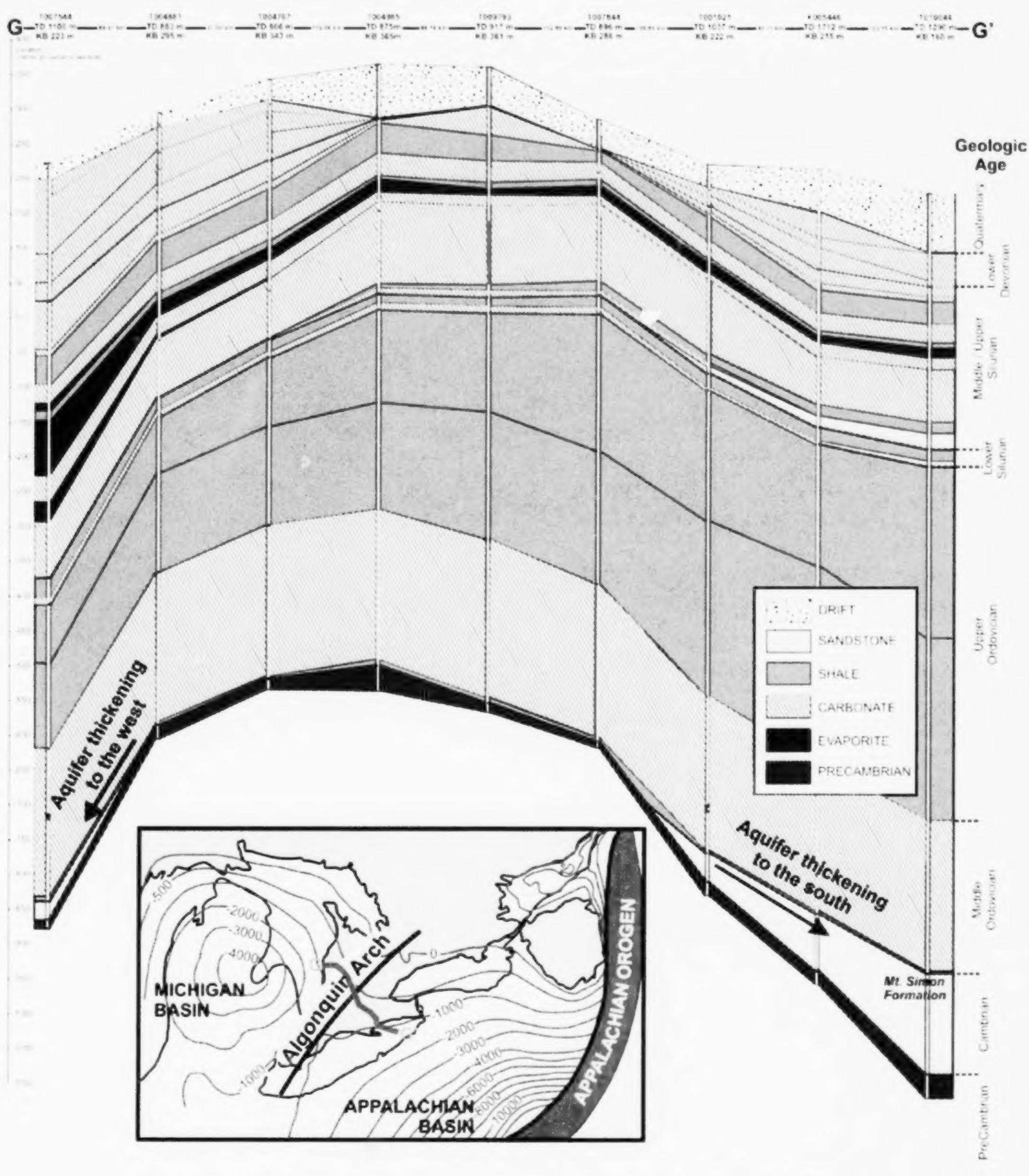


Figure 9. Geologic cross section across the Algonquin Arch in southern Ontario. Inset shows thickness of Paleozoic sedimentary rocks in metres. Paleozoic rock units thicken to the west and south on either side of the arch (modified from Armstrong and Carter 2006a,b).

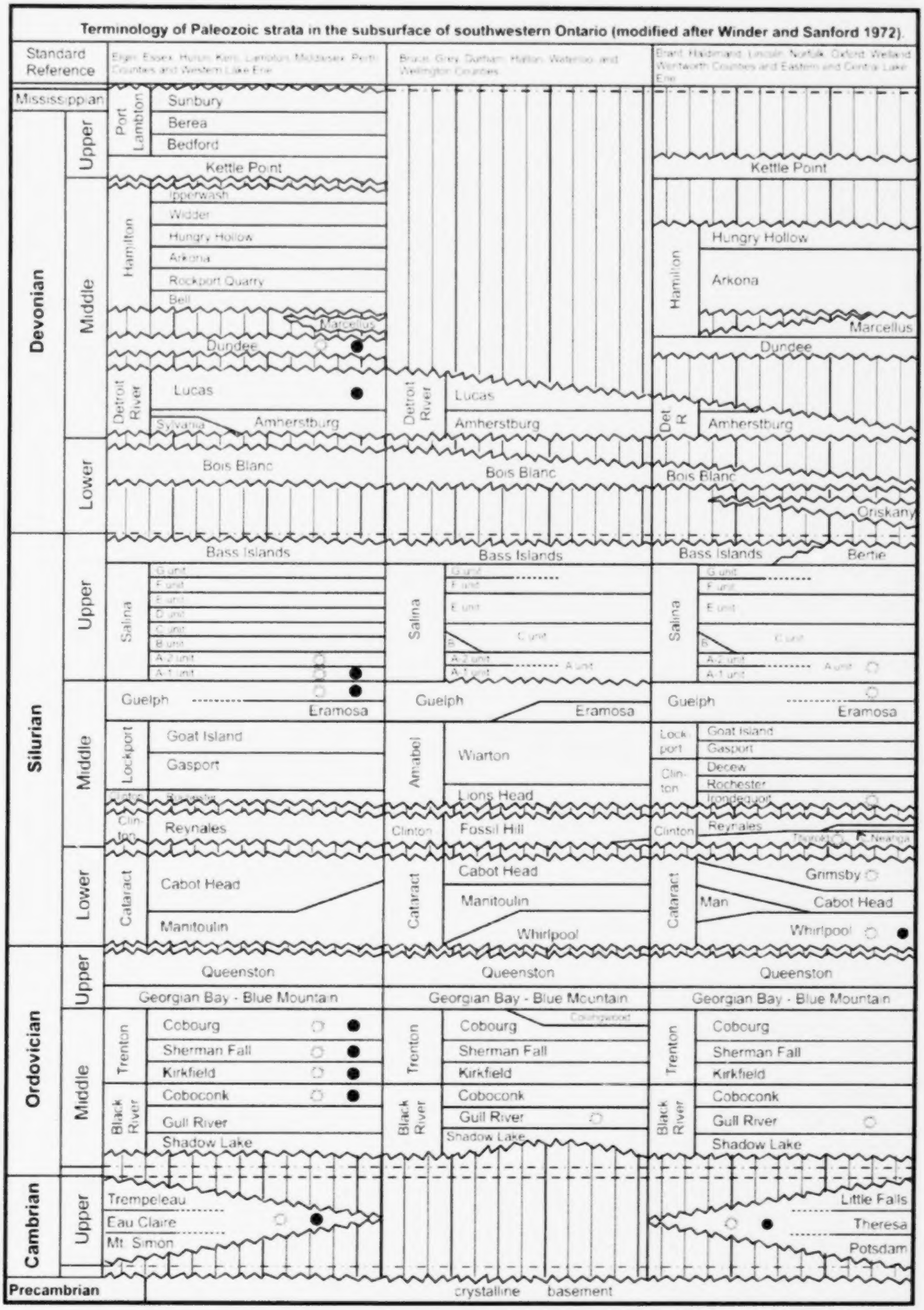


Figure 10. Terminology of Paleozoic strata for southwestern Ontario (updated from Winder and Sanford 1972). See Figure 6 for explanation of symbols.

Geologic Options for Carbon Dioxide Storage in Ontario

The feasibility and potential for geological sequestration of CO_2 in Ontario is directly related to geology since in the absence of suitable geologic features all other technical criteria are irrelevant. Thus the following analysis summarizes the potential for geological storage of CO_2 and identifies possible options for further study. Options considered are coal beds and organic shales, oil and gas reservoirs, saline aquifers, and salt caverns.

Coal Beds and Organic Shales

While injection of CO_2 into deep coal seams to enhance the production of coal bed methane is being tested in other parts of North America, no deep coal seams are present in Ontario. Thus, this option is not considered further in this analysis.

In Kentucky, Devonian-aged, low permeability, organic gas-rich shales are being studied as a potential site for CO_2 storage (Nuttall et al. 2005). Devonian shales within Ontario are too shallow (200 m and less) to provide an adequate pressure and temperature regime for the storage of CO_2. Organic-rich shales at the base of the Blue Mountain Formation (Figure 10) locally occur at depths greater than 800 m but their suitability for CO_2 storage has not been studied.

Oil and Gas Reservoirs

Accumulations of oil and gas occur in porous and permeable rock and are known as reservoirs or pools. The key features of a good reservoir are high porosity and permeability to allow the hydrocarbons to migrate and pool in the rock and the presence of an impermeable layer above the porous rocks to form a trap or seal. Without the latter, due to its buoyancy relative to water, any oil or gas in the rock would migrate upwards towards the surface. The same holds true for CO_2 in the subsurface as it is also buoyant in water (at shallow depths). Due to their porosity and permeability, sandstones and dolostones tend to be the best reservoir rocks while limestones and shales tend to act as a seal. The same geological characteristics that form good oil and gas reservoirs also make them excellent candidates for CO_2 storage.

Oil and gas reservoirs in Ontario are found at a variety of depths and in different rock types. Common reservoirs include Cambrian sandstones (at depths of 800 to 1200 m), Ordovician carbonates (800 to 900 m), Silurian carbonates (500 to 700 m and 350 to 450 m), and Devonian carbonates (110 to 140 m) all of which occur in southwestern Ontario. A total of 262 oil and gas pools occur in southern Ontario with cumulative production of 1.3 trillion cubic feet of natural gas and 85 million barrels of oil (Carter et al. 2006) (Figure 11). To date neither oil nor natural gas have been discovered in the Hudson Bay and Moose River basins or in eastern Ontario.

Studies for the potential storage of CO_2 in depleted oil and gas reservoirs in Ontario or for use of CO_2 for enhanced oil recovery have not been completed. Shafeen et al. (2004a) considered that the shallow depth of the reservoirs, large number of unplugged wells, and limited pore volume renders this option unfeasible in Ontario. Individual reservoirs may prove to be technically suitable but would require further study to confirm.

Salt Caverns

Injection of CO_2 into salt caverns is being considered for both permanent and temporary storage in major salt-producing formations in other parts of the world. Salt is impermeable to supercritical CO_2 and therefore provides an ideal trapping mechanism for the gas (Dusseault et al. 2001). Ontario produces large quantities of salt from solution mining operations and has a number of abandoned caverns where salt extraction no longer occurs. Unfortunately, the Salina Group from which the salt is produced occurs at too shallow a depth to provide the necessary conditions for storage of large quantities of CO_2. Depth to salt beds beneath Lake Huron is unknown but if deep enough there may be potential for construction of salt caverns for storage beneath the lake.

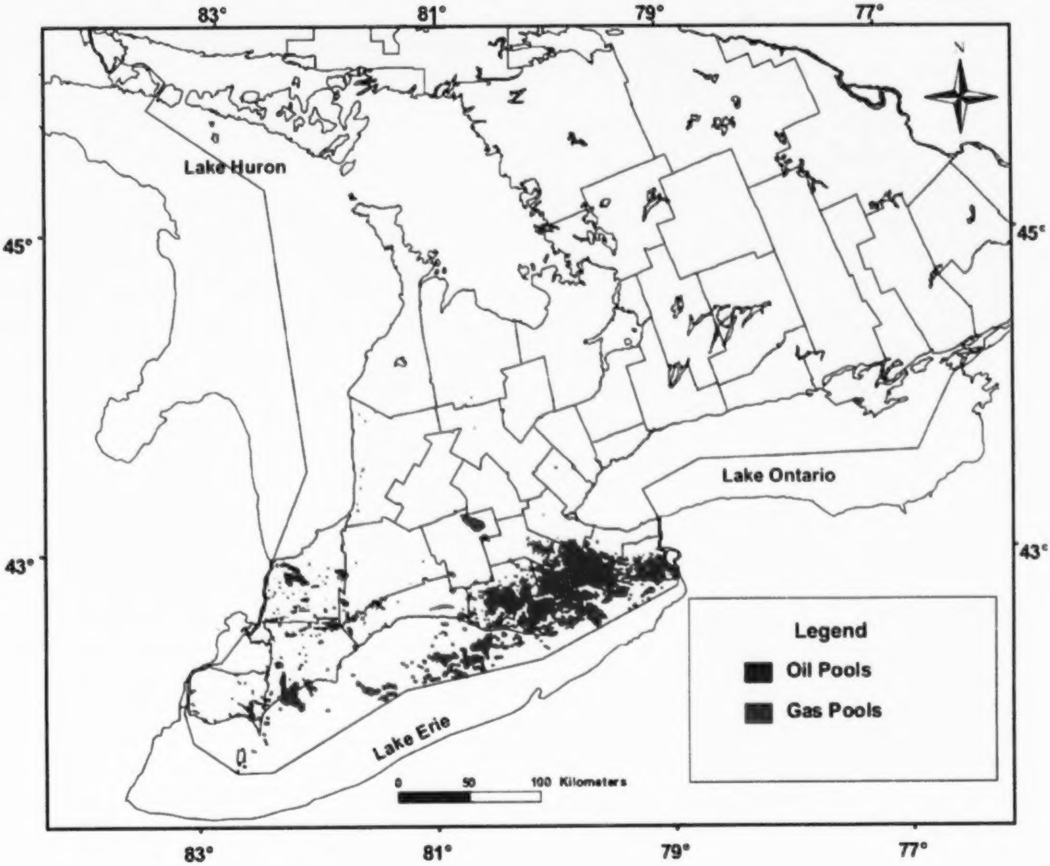


Figure 11. Known oil and gas pools of Ontario (derived from Carter et al. 2006).

Saline Aquifers

When a porous rock contains water instead of oil or gas it is known as an aquifer. Two types of aquifers can be distinguished in southern Ontario; deep saline aquifers in the Paleozoic bedrock and freshwater aquifers in the unconsolidated sediments (glacial drift) overlying the Paleozoic and Precambrian bedrock and locally in near-surface Paleozoic bedrock. Freshwater aquifers are shallow, recharged by meteoric waters, and sources of drinking water in Ontario and therefore are not candidates for CO_2 storage. Saline aquifers occur within the sedimentary bedrock in the basins of southern Ontario and Hudson Bay, generally at depths greater than a few tens of metres or wherever the bedrock is covered by thick accumulations of glacial drift. Saline aquifers are usually isolated from freshwater aquifers. While all porous rocks in the subsurface of southern Ontario are filled with water (or locally with hydrocarbons) only a few of these form porous layers thick enough or regionally extensive enough to comprise significant aquifers. Waters within these deep aquifers contain elevated concentrations of salt and/or sulphur and are generally not suitable for drinking, irrigation or other domestic purposes. Therefore, injection of CO_2 should not pose a risk for future use and in fact CO_2 is naturally present in groundwater (Hutcheon and Abercrombie 1990, Ballentine et al. 2001).

Shafeen et al. (2004a) assessed saline aquifers within all the sedimentary basins of Ontario to determine the best candidates for CO_2 storage. Paleozoic sedimentary rocks in the Hudson Bay and Moose River basins and in eastern Ontario were deemed either too shallow to provide the conditions for CO_2 storage or too distant from large point sources of CO_2 to make them viable options. Only saline aquifers in the Michigan and Appalachian basins in southern Ontario were considered suitable.

Within the Michigan and Appalachian basins the Upper Cambrian age Mt. Simon Formation is considered the best candidate for CO_2 storage. Most of the other sedimentary formations are too shallow. The Mt. Simon Formation (Figure 12) is a saline aquifer consisting of regionally extensive, porous sandstone underlying large parts of southern Ontario and the neighbouring U.S. states. It occurs close to point sources of CO_2 generation (Table 2) and an established pipeline infrastructure. The formation thickens to the west under Lake Huron and into Michigan as part of the Michigan Basin and to the south under Lake Erie and the adjacent states within the Appalachian Basin and pinches out over the top of the Algonquin Arch. The formation is overlain by dolomitic and sandy shales of the Shadow Lake Formation and non-porous limestones of the Gull River Formation, which serves as a cap rock (Figures 10 and 12). The Shadow Lake Formation is overlain by an additional 600 m or more of non-porous Ordovician limestones and shales, which form an excellent barrier to upward movement of fluids (Figures 6 and 10).

Shafeen et al. (2004a) divided the available storage within the Mt. Simon Formation into two zones on either side of the Algonquin Arch, which separates the Michigan and Appalachian Basins (Figure 7). The northern zone (6,250 km^2) consists of the southern half of Lake Huron and the northern part of Lambton county. The southern zone (9,525 km^2) extends into Lake Erie and includes parts of Essex, Lake St. Clair, Kent, Elgin, and Haldimand-Norfolk counties. Calculated storage capacities are based on the lateral extent of the formation, estimates or assumptions of formation thickness, porosity, and permeability, and assumptions about potential CO_2 saturation within these two areas.

Capacity of the Mt. Simon Formation

Shafeen et al. (2004a) estimate that the Mt. Simon Formation saline aquifer could be capable of storing 289 million tonnes (Mt) of CO_2 in the northern zone and 442 Mt in the southern zone. These calculations were based on an assumed average porosity of 10% with an assumed average thickness of 31 m. No detailed thickness maps were prepared and no drill core or cuttings were examined. The capacity estimates are also based on estimates/assumptions of the salinity of the formation (which controls the CO_2 solubility) and of the achievable sweep efficiency (effectiveness of the injected CO_2 contacting the pore space of the aquifer). The estimates of storage capacity are very sensitive to the assumed values for porosity, permeability, sweep efficiency, and solubility. In the southern storage zone, for example, increasing the porosity from 10 to 25% results in 1,104 Mt storage capacity while decreasing it to 5% reduces the capacity to 220 Mt. The greatest increase in storage capacity can be realized by increasing the sweep efficiency. This may be possible with multiple injection locations and better technology. However, better characterization of the Cambrian reservoirs is clearly needed to accurately estimate the potential for long-term storage of CO_2 to justify the large capital expenditures necessary for CO_2 capture.

Carbon Dioxide Injection and Migration

From a geological perspective, the ideal injection points for CO_2 storage in Ontario lie near the Canada-U.S. border, beneath Lake Erie and Lake Huron (Figure 12). Here, the Mt. Simon formation is thickest, deepest, and furthest from producing oil and gas pools on land. Offshore injection would require the construction of a pipeline on the bed of the lake, injection wells drilled through the lake bottom, and possibly a permanent platform on the lake.

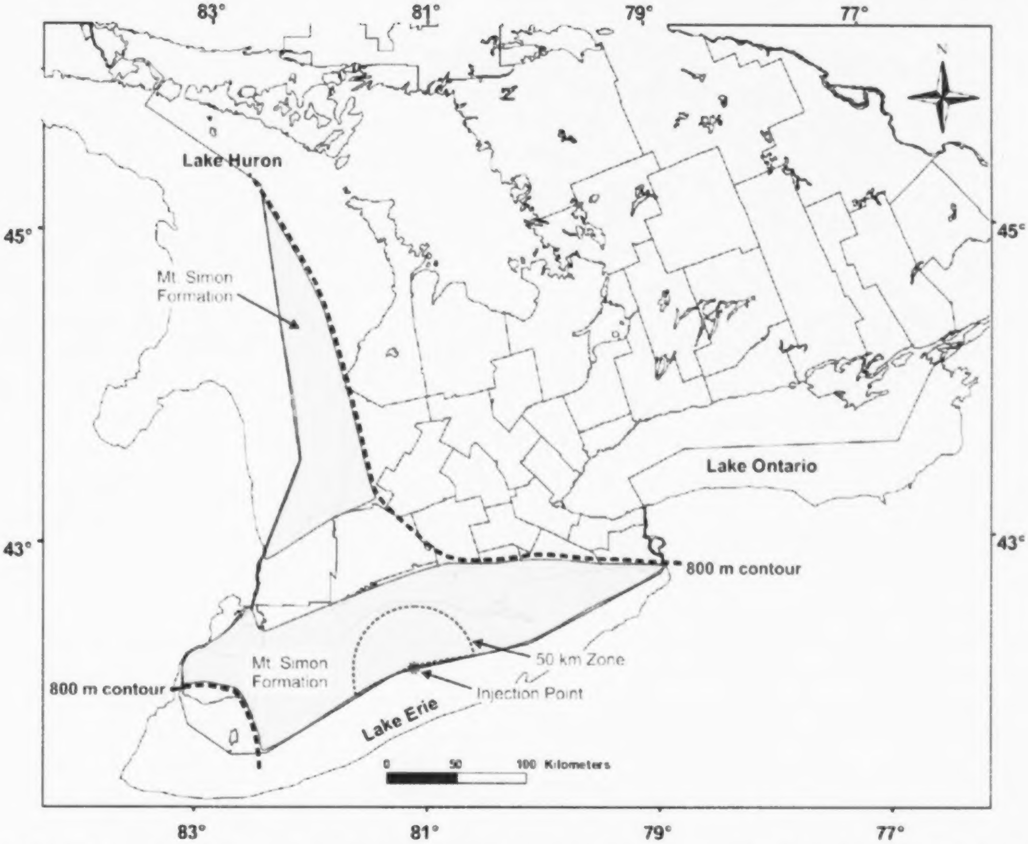


Figure 12. Extent of saline aquifers in the Mt. Simon Formation in southern Ontario and possible CO_2 injection points (after Shafeen et al. 2004a).

Once the CO_2 is injected into the formation it will migrate away from the injection point due to buoyancy differences with the formation waters and by diffusion. The buoyancy difference will force the lighter CO_2 plume to the north, while diffusion will radiate outwards in all directions. Upward migration will continue until the plume encounters the cap rock of the Shadow Lake Formation. The plume will then spread laterally along the contact and continue to be dissolved in the formation waters. Based on modelling studies cited by Shafeen et al. (2004a) it is estimated that the plume will not migrate more than 25 to 50 km before it is completely dissolved in the formation waters. This could take upwards of thousands of years. Due to the upward movement of the dissolved plume, chances of CO_2 migrating to the American side of the border are minimal.

Several oil and gas reservoirs occur within the Mt. Simon Formation or other Cambrian-age formations, but only one of these occurs beneath Lake Erie. The other pools are found beneath onshore areas along the north shore of Lake Erie and lie more than 50 km from the potential injection site. However, because the formation occurs at shallower depths over the Algonquin Arch, detailed studies are necessary to examine and eliminate the possibility of migration above the critical depth of 865 m.

Infrastructure for well drilling and pipeline construction already exists on Lake Erie. Currently more than 500 active gas wells are operated by Talisman Energy on Lake Erie and 1,500 km of natural gas pipeline have been installed on the lake bed to service the gas industry. These activities boast an excellent safety and environmental record.

Risks

The principal risk associated with storing CO_2 in the subsurface is the potential for escape to the surface via fractures, faults or existing wellbores. Several existing faults have been identified beneath Lake Erie (Figure 13). No data on the occurrence or distribution of faults are available for Lake Huron. Precise locations and vertical extent of these faults need to be more accurately determined as some lie within 50 km of the proposed injection point and might provide a pathway for upward or lateral movement of CO_2 and possible escape to the atmosphere. No studies of fluid movement along these faults have been conducted. None of these faults are known to be associated with any recent seismic activity.

More than 50,000 wells have been drilled in Ontario for oil and gas since 1858. Many of the earliest wells are unknown or poorly documented. Shafeen et al. (2004a) have identified 189 wells with depths greater than 700 m with no plugging records that could compromise the integrity of the Mt. Simon Formation, but none of these lie beneath either Lake Erie or Lake Huron. Older plugged wells may be suspect due to potential deterioration of the plugging material in the presence of elevated levels of CO_2. While it appears that all of the wells fall outside of the 50 km estimated migration path, it is necessary to accurately map the well locations and status and determine the potential effects of increased formation pressure and CO_2 reactivity on older wells as well as environmental consequences should a failure occur.

Another important concern arises when and if the pressure of the formation drops below the critical pressure needed to maintain the supercritical phase of CO_2. If the CO_2 plume crosses the critical pressure threshold at 865 m, it will vapourize, reducing the storage capacity, and possibly accelerating movement of the plume. The depth of the Shadow Lake and Gull River cap rocks decrease to 865 m at distances of 75 to 120 km from the injection point identified by Shafeen et al. (2004a) on Lake Erie. This is beyond the 50 km zone where the CO_2 is expected to be completely dissolved within the formation waters.

Figure 13. Major geologic fault lines in southwestern Ontario (compiled from Brigham 1971; Bailey Geological Services 1984, Bailey and Cochrane 1984, 1985, 1986).

While moderate seismic activity occurs in eastern Ontario and western Quebec, seismic activity in southwestern Ontario is low (Figure 14). Therefore, there is little chance of major fault reactivation which could allow CO_2 gas to escape to the surface or damage the gas pipeline infrastructure.

Infrastructure and Costs

The cost of implementing and maintaining a carbon capture and geological storage infrastructure is significant. According to Metz et al. (2005) capture costs would be in the range of US$15 to $75/t of CO_2, with transportation ranging from US$1 to $8/t and storage between US$0.5 to $8/t. Pierre Alvarez, president of the Canadian Association of Petroleum Producers, has recently estimated that the costs would range from Cdn$30 to $50/t (Geddes 2006).

An estimate of capital costs of CCS in Ontario was prepared by Shafeen et al. (2004b) based on implementation for just one of the eight 500 MW coal-fired generators from the Nanticoke plant. This cost analysis looked at collection, two transportation options, and injection requirements for the southern storage zone in Lake Erie. Estimates of capital costs range from US$257 to 397 million, with an average annual maintenance cost of about 7.5% of the capital investment. Subsequent to completion of this study the Ontario government announced plans to close the Nanticoke plant.

Electricity production costs associated with new plants designed with CCS facilities are estimated to be 20 to 85% higher than conventional plants (Metz et al. 2005). Significant tax and/or regulatory incentives will be needed in the initial stages of a CCS program to promote deployment. Eventually, however, costs are expected to decrease as the technology is developed and improved. Potential sale of CO_2 for industrial uses and for EOR has been demonstrated at the Weyburn oil field in Saskatchewan. These options may offset some of the capital and operating costs associated with the CCS infrastructure.

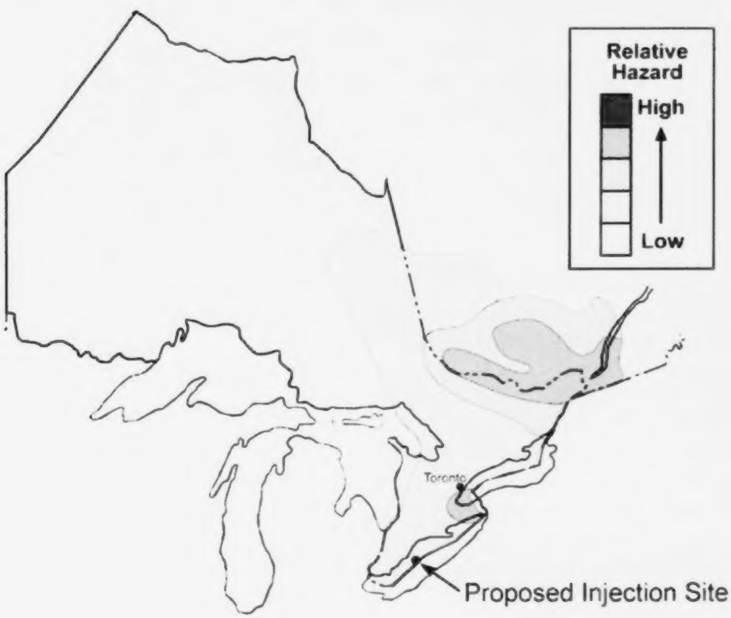


Figure 14. *Relative seismic hazard in Ontario (data from Natural Resources Canada 2006a).*

Carbon Capture and Storage Initiatives in Ontario

An information workshop on CO_2 capture and geological storage was held on February 16, 2006 in Toronto. This workshop was sponsored by the MNR, Ministry of Northern Development and Mines (MNDM), Natural Resources Canada (NRCan), and the Alberta Research Council. The advisory group consisted of NRCan, Alberta Research Council, University of Waterloo, Ontario Power Generation, Delphi Group, Integrated CO_2 Network (ICO_2N), EnergyNet, and the Battelle Memorial Institute of Ohio, with the Alberta Research Council as the scientific lead. The workshop provided an excellent forum to discuss CCS specifically for Ontario by some of the top scientists in Canada and provided insight into options that could be adopted in the future by Ontario's government and energy sector.

The ICO_2N, in consultation with government, non-government organizations, and respected researchers, seeks to harness the broad range of expertise and resources required to fast-track development of a national CCS system. This network would combine investments in infrastructure and technology with the development of a CO_2 marketplace, supported by the appropriate Federal and Provincial policy, government and private funding, and an effective regulatory framework. ICO_2N represents key industries ranging from minerals and metals refining, fertilizer production and electrical generation, to petroleum extraction and refining. If CCS is pursued on a large scale, there are significant advantages to planning and constructing an integrated system of CO_2 capture, transport, and storage. This concept has been the primary focus of ICO_2N in western Canada and may be applicable to CCS in southwestern Ontario.

Carbon dioxide pipelines use commercially available and tested technology. They are not significantly different in construction or operation from pipelines that transport natural gas or other hydrocarbons – and they have been used for over 30 years in the southern U.S., where the technology has proven to be reliable and safe. Potentially, a CCS network could be developed between Hamilton, Nanticoke, and Sarnia in close proximity to storage locations and to large final emitters. As a first stage, this network could use the storage potential under Lake Erie and Lake Huron and in later years expand to tie in storage locations in Michigan, Ohio, and Pennsylvania, where a significant effort is underway by U.S. state and federal agencies to search for suitable sequestration sites. A precedent for international transport of CO_2 has already been established with the Weyburn project in Saskatchewan, where CO_2 from North Dakota is being transported to and stored in southern Saskatchewan.

A CCS network could connect the major point sources in southwestern Ontario and have two lines leading to storage reservoirs. One of these lines would head north to the storage basin under Lake Huron and the other could feed into the storage basin to the south under Lake Erie. The main connecting line could be built as a manifold pipeline with the capacity to flow in either direction, depending on the input of CO_2 supply volumes and operation of storage locations. Such a model would mirror the system proposed to handle CCS in Western Canada. The primary difference would be higher overall costs of CCS activity in Ontario. Pipeline costs in the highly urbanized southwestern Ontario region are expected to be much higher than in western Canada. Also, the lack of a suitably sized oil production system would mean very little revenue for the CCS system from the sale of CO_2 for EOR. These factors would lead to higher CCS costs in Ontario compared to what might be expected in Alberta and Saskatchewan.

While Ontario's capacity to geologically store CO_2 may ultimately be limited by the maximum 1,400 m thickness of sedimentary rocks, significant opportunities for carbon sequestration exist in the Midwest region of the U.S. More than 475 Gt capacity are estimated for the Midwest U.S. including Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia. Ultimately Ontario may need to tap into this capacity.

Next Steps

The study by Shafeen et al. (2004a) is the only investigation on the potential for geological sequestration of CO_2 in Ontario and they recommend additional research before testing can occur. Only 29 wells with varying amounts of data penetrate the Mt. Simon formation underlying Lake Erie and no wells have been drilled in Lake Huron. Their study did not include analysis of seismic data, drill core or drill cuttings, nor did they perform any porosity or permeability measurements, or generate any structure or thickness maps as this was beyond the scope of their research. Critical parameters, such as average porosity and thickness, were assumed or extrapolated over very large distances. They also did not consider other Cambrian formations that may have potential for CO_2 storage. Accurate mapping of faults and fractures and determining abandoned well integrity are necessary to assess the risks associated with gas injection and storage. In addition, the potential impact on undiscovered hydrocarbon reserves needs to be assessed as well as the possibility of using CO_2 injection for EOR.

A scientific study is proposed to follow up on the study by Shafeen et al. (2004a,b). This multi-year study would focus on deep formations beneath and adjacent to Lake Erie and Lake Huron, identified by Shafeen et al. (2004a) to have the best potential for permanent geological storage of large volumes of CO_2. This could be a joint venture between the MNR Petroleum Resources Centre and the Ontario Geological Survey of MNDM. Potential partners include Natural Resources Canada, the Midwest Regional Carbon Sequestration Partnership (MRCSP) in the U.S., and the oil and gas, petrochemical, and electricity industries in Ontario with opportunities for cost-sharing and in-kind contributions. Major elements of the proposal are:

- Year 1: *Science and Analysis* – Analysis of global state of knowledge through literature search, attendance at international meetings/workshops/conferences, membership/participation in MRCSP, financial contribution to ongoing research at MRCSP and access to past research, preliminary geological mapping using available data and staff, development of detailed research plan and research team, and identification of related policy, regulatory, environmental issues.
- Years 2 and 3: *Research and Innovation* – Implement program of scientific study, including drilling to acquire core and water samples for analysis and testing of porosity, permeability, petrography, and geochemistry; injection tests to measure permeability and injection rates; modelling, acquisition and interpretation of regional aeromagnetic data; 2D and 3D seismic acquisition, processing and interpretation; remapping of structure, isopach and faults, and volume calculations.
- Year 4: *Analysis and Recommendations* – Conduct data analysis and interpretation, write reports and provide recommendations for test injection site.
- Year 5+: *Application of Knowledge* – Proceed with trial injection – this is beyond the scope of the current proposal.

The results of the project would be more precise estimates of storage volumes and potential injection rates, rock characteristics, cap rock integrity; maps of faults and fractures to assess risk of leakage; and a model for migration routes and thus knowledge of the best potential injection sites. If CCS is to be used in Ontario, such a project is a necessary first step in designing a safe and effective storage strategy and justifying the much larger expenditures required to construct the CO_2 capture and transportation infrastructure.

Summary

Carbon sequestration has been identified by the IPCC as an important component of global efforts to manage CO_2 emissions and mitigate their contribution to global warming. Considerable knowledge of the science and technology of CCS has already been acquired. The technology is already in use by the oil and gas industry but no full-scale operations exist at other types of industrial facilities. Some uncertainties related to cost and reliability of capture technology remain, with research now underway to address these issues. Nonetheless, these issues will likely be resolved and the technology could then be implemented in other industries such as power generation.

Carbon capture and storage is very costly and will probably not be voluntarily implemented by industry. One approach to encourage its use is to place a value on emissions, possibly through regulatory and/or tax incentives. The lack of a clear government policy and regulatory framework related to carbon emissions and CO_2 capture and storage is also a sticking point for industry (Collison 2007).

Further research is necessary to assess Ontario's geological capacity and suitability for storage, identify possible risks, and find the best potential sites for injection of CO_2 into the subsurface. This is costly and time-consuming research but would help identify and resolve associated policy and regulatory issues. The United States, through its regional carbon sequestration partnerships, has been involved in this type of research since 2003 and other Canadian provinces are already involved as partners. Ontario could collaborate on these various initiatives.

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